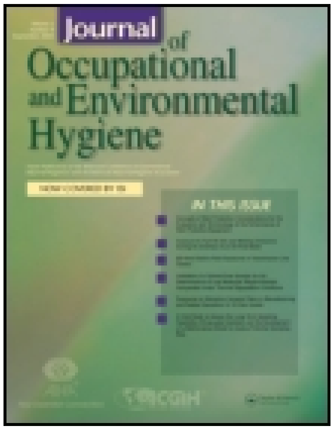
This article was downloaded by: [Florida Atlantic University]
On: 24 November 2014, At: 11:00
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Journal of Occupational and Environmental Hygiene
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/uoeh20

N95 Filtering Facepiece Respirator Deadspace Temperature and Humidity

Raymond J. Roberge [a] , Jung-Hyun Kim [a] & Stacey Benson [a]
[a] National Institute for Occupational Safety and Health, National Personal Protective Technology Laboratory , Pittsburgh , Pennsylvania
Accepted author version posted online: 02 Feb 2012.Published online: 13 Mar 2012.

To cite this article: Raymond J. Roberge , Jung-Hyun Kim & Stacey Benson (2012) N95 Filtering Facepiece Respirator Deadspace Temperature and Humidity, Journal of Occupational and Environmental Hygiene, 9:3, 166-171, DOI: 10.1080/15459624.2012.660428

To link to this article: http://dx.doi.org/10.1080/15459624.2012.660428

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the "Content") contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at http://www.tandfonline.com/page/terms-and-conditions

Journal of Occupational and Environmental Hygiene, 9: 166–171
ISSN: 1545-9624 print / 1545-9632 online
DOI: 10.1080/15459624.2012.660428

N95 Filtering Facepiece Respirator Deadspace Temperature and Humidity

Raymond J. Roberge, Jung-Hyun Kim, and Stacey Benson

National Institute for Occupational Safety and Health, National Personal Protective Technology Laboratory, Pittsburgh, Pennsylvania

Downloaded by [Florida Atlantic University] at 11:00 24 November 2014

The objective of this study was to determine the levels of heat and humidity that develop within the deadspace of N95 filtering facepiece respirators (N95 FFR). Seventeen subjects wore two models each of N95 FFR and N95 FFR with an exhalation valve (N95 FFR/EV) while exercising on a treadmill at a low-moderate work rate for 1 and 2 hr in a temperate ambient environment. FFR deadspace temperature and relative humidity were monitored by a wireless sensor housed within the FFR. Each FFR was weighed pre- and post-testing to determine moisture retention. After 1 hr, FFR deadspace temperature and humidity were markedly elevated above ambient levels, and the FFR deadspace mean apparent heat index was 54°C. N95 FFR/EV use resulted in significantly lower deadspace temperatures than N95 FFR ($p = 0.01$), but FFR deadspace humidity levels were not significantly different ($p = 0.32$). Compared with the first hour of use, no significant increase in FFR deadspace heat and humidity occurred over the second hour. FFR mean moisture retention was < 0.3 grams over 2 hr. N95 FFR/EV offer a significant advantage in deadspace heat dissipation over N95 FFR at a low-moderate work rate over 1 hr of continuous use but offered no additional benefit in humidity amelioration. Moisture retention in N95 FFR and N95 FFR/EV is minimal after 2 hr of use.

[Supplementary materials are available for this article. Go to the publisher's online edition of Journal of Occupational and Environmental Hygiene for the following free supplemental resource: a file containing N95 filtering facepiece respirator deadspace mean RH and temperature recordings for 17 subjects treadmill exercising at 5.6 Km/H over 1 hour.]

Keywords deadspace, exhalation valve, humidity, N95 filtering facepiece respirators, temperature

Correspondence to: Raymond J. Roberge, NIOSH-NPPTL, 626 Cochrans Mill Road, Pittsburgh, PA 15236; e-mail: dtn0@cdc.gov.

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

INTRODUCTION

Filtering facepiece respirators (FFR) are the most commonly utilized respirators in U.S. private industry and in the health care environment. The most popular version, the N95 FFR model, filters out at least 95% of $\geq .3$-μm particles during testing at a continuous flow rate of 85 L/min, when tested in a laboratory.[1,2] The barrier property of respiratory protective equipment (RPE) inhibits, to variable degree, that portion (∼10%) of the body heat burden that is normally eliminated via the respiratory tract.[3] Also, the internal milieu (deadspace) of the RPE serves as a repository for a portion of the moisture and heat that is expelled with each exhalation and subsequently re-inspired with succeeding inhalations.[4]

In addition, heat convection and sweat evaporation from facial skin covered by RPE (approximately 2% of body surface area) are impeded,[5] thereby further increasing the RPE deadspace temperature and humidity. These actions, along with the contribution (∼10%) of the head region to heat dissipation,[6] conspire to create sensations of increased facial heat, which is a frequently voiced complaint by wearers of FFR.[7–11] This thermal discomfort sometimes leads to premature removal of these devices, thereby subjecting the wearer to the potential inhalation of harmful airborne particulates or infectious agents.[12] In an attempt to ameliorate FFR thermal effects, some FFR are equipped with exhalation valves (EV) that, by bypassing the filter media, allow for decreased exhalation resistance and a decrease in FFR deadspace heat and humidity.[13]

Although some studies have evaluated the levels of heat and humidity that develop in the deadspace of various types of FFR,[9,14,15] there are scant data with respect to N95 models[7,8] or on the impact of N95 FFR with EV (N95 FFR/EV) on these parameters. Such information could be useful to stakeholders, such as researchers evaluating the overall contribution of N95 FFR to body heat, manufacturers who would be interested in the development of N95 FFR with enhanced heat dissipation properties, and N95 FFR users working in warm, humid environments and concerned about any additional thermal burden. The current study, part of a broader investigation by the National Institute for Occupational Safety and Health (NIOSH) evaluating the use of RPE,[16] examined the levels of temperature and relative humidity (RH)

attained in the deadspace of N95 FFR and N95 FFR/EV.

MATERIALS AND METHODS

Twenty-one subjects were recruited for the study and 20 were enrolled. One recruited subject experienced an FFR-related anxiety reaction during fit testing and was excluded from participation in the study. Data were incomplete for three subjects; therefore, data presented are from 17 healthy subjects (11 men, 6 women), all of whom were non-smokers, and 10 with no prior experience wearing N95 FFR. Subject descriptive statistics (standard deviations) included: age 22.6 years (2.8), height 175.7 cm (9.7), body weight 79.3 kg (16.7), body mass index 25.6 kg/m^2 (4.2). All subjects were given a screening physical examination by a licensed physician, passed a urine test for drugs of abuse, and, for women subjects, tested negative for pregnancy. The study was approved by the NIOSH Human Subjects Review Board, and all subjects provided oral and written informed consent.

Subjects were required to pass a respirator quantitative fit test[(17)] for each of two flat-fold N95 FFR models (3M 9210 and 9211; 3M Corp., St. Paul, Minn.) and each of two cup-shaped models (Moldex 2200 and 2300; Moldex, Culver City, Calif.) to participate in the study. Two of the models (3M 9211, Moldex 2300) were N95 FFR/EV. These models were selected for the study because their counterpart N95 FFR models without EV are similar in all respects save for the presence of the EV. Other features of the tested FFR can be found in Table I. FFR were not pre-conditioned, and testing was carried out in a physiology laboratory during a 3-month period of winter in the northern hemisphere. Subjects were attired in T-shirts, athletic shorts or sports pants, and athletic shoes and walked on a treadmill at a low-moderate work rate (5.6 km/h; 0° inclination) continuously for a period of 1 hr with a randomly assigned FFR (17 subjects $\times$ 4 tests = 68 total tests). For each subject, one of the FFR tests was randomly assigned as a 2-hr test to assess longer periods of wear (17 tests). There was a minimum respite of 30 min between any successive tests. No subject was allowed to exceed 5 hr (i.e., 27.35 km) of treadmill exercise in any single day of testing.

FFR deadspace temperature and RH were measured every 20 seconds (user defined response time) by an I-Button semiconductor temperature and RH sensor (I-Button, Dallas, Texas) that incorporates a real-time clock, memory, and 3V lithium battery encased in a small (16 $\times$ 6 mm) stainless steel can (temperature range –40°C to 85°C). I-Button was selected for the study because of its wireless capability that obviates the need to instrument the FFR with wires or access ports for data collection, and its small dimensions that allow for easy fit within the deadspace of the FFR. I-Button has previously been shown to be useful in the evaluation of other personal protective equipment with deadspace.[(18)] Prior to the study, pilot I-Button sensor air temperature and RH data were compared over 1 hr with concurrent data from a DewMaster chilled mirror hygrometer (EdgeTech, Marlborough, Mass.) that was calibrated to standards traceable to the National Institute of Standards and Technology, and a strong correlation was noted (r = 0.99). For the study, an I-Button was taped to the peripheral right perioral region of the inner surface of the FFR (Figure 1). All FFR were weighed immediately pre- and post-testing on an ACCU-6201 calibrated analytical balance (Fisher Scientific, Waltham, Mass.) to determine moisture retention.

Downloaded by [Florida Atlantic University] at 11:00 24 November 2014

TABLE I. Features of the N95 Filtering Facepiece Respirators Used in the Study

	Filtering Facepiece Respirator			
	Moldex 2200	Moldex 2300	3M-9210	3M-9211
Features Shape	Cup Shaped		Flat Fold	
Exhalation valve	No	Yes	No	Yes
Outer layer	Hydrophobic		Hydrophobic	
Middle layer	Hydrophobic		No middle layer	
Inner layer	Hydrophobic		Hydrophobic	
Tethering devices	Two rubber bands		Two elastic straps	
Surface area (cm^2)	211.40	217.60 202.20^A	222.11	227.35 214.07^A
Weight (gm)	14.3 (±0.7)	19.6 (±0.4)	9.6 (±0.1)	13.9 (±0.1)
Breathing resistance (mm H_2O)^B	11.6 (±1.0)	12.2 (±0.7)	8.6 (±0.4)	9.0 (±0.4)
Static dead space (mL)	280	290	375	360

^{A}Inner surface area minus exhalation valve area.
^{B}Measured with a TSI 8130 Filter Tester.
Note: Moldex models are integrated with a mesh plastic support skeleton (nonfiltering) covering the entire outer surface and between the inner and middle layers.

FIGURE 1. I-Button temperature and humidity sensor affixed to the internal surface of an N95 filtering facepiece respirator.

Statistical Analysis

The dependent variables (RH and temperature) were first calculated as means and standard deviations in 5-min intervals for each individual subject across four experimental conditions. For the analysis of 1-hr trials, the variables were analyzed by a two-way repeated measures analysis of variance (ANOVA) (Time × Type) to determine main effect and interactions with the Greenhouse-Geisser correction for sphericity to designate a level of significance. For a significant F-ratio obtained from repeated measures, post hoc pair-wise comparison was then performed with the least significant difference (LSD) adjustment. For comparison of RH and temperature responses between 1- and 2-hr trials, independent sample t-tests were carried out to compare the variables at the following time points: 0 min, 60 min, and 60 vs. 120 min. In this analysis, trial conditions were rearranged as respirator without exhalation valve (Moldex 2200 + 3M 9210) and with exhalation valve (Moldex 2300 + 3M 9211). One subject's 2-hr data were missing due to equipment failure (n = 16 for 2-hr analysis). Levene's test was also performed to confirm the assumption on equal variances in the two trial conditions for the t-test. A statistical significance was accepted when $p < 0.05$ and all analyses were performed using a statistical software package (SPSS version 18; IBM, Somers, N.Y.).

RESULTS

All 17 subjects completed all phases of the study. The mean laboratory temperature, RH, and barometric pressure (corrected for standard temperature and pressure) during the study period averaged, respectively, 21.45°C (0.78), 23.55% (7.96), and 738.18 mm H_2O (5.55). There was no significant difference at 1 hr in mean increases in weight of FFR (0.15 grams ±0.26) and FFR with EV (0.26 grams ±0.39) (p = 0.26), nor at 2 hr (FFR 0.21 grams ±0.33, FFR with EV 0.28 grams ±0.25) (p = 0.83).

FFR Deadspace Humidity

There were no significant differences in baseline FFR deadspace mean RH readings among trials, but deadspace RH increased as a function of time ($F = 90.770$; $p < 0.001$) (Table II; Figure 2). The type of FFR had no significant effect on RH ($F = 1.192$; $p = 0.32$), nor did the interaction of FFR type and time ($F = 1.339$, $p = 0.09$). Deadspace RH values at 120 min did not differ significantly from the 60-min values ($p>0.05$) (Table II).

FFR Deadspace Temperature.

There were no significant differences in deadspace baseline mean temperature readings (online supplementary data Table S-1), but the FFR type was significantly associated with temperature over the course of 1 hr ($F = 4.62$; $p = 0.01$) (Figure 2). Higher mean FFR deadspace temperatures were observed for the Moldex 2200 compared with the Moldex 2300 (p = 0.04), the 3M 9210 compared with the 3M 9211 (p = 0.001), and the 3M 9210 compared with the Moldex 2300 (p = 0.02)

TABLE II. Comparison of 1-Hr and 2-Hr FFR Deadspace Temperature and RH Readings

		Combined N95 FFR Trials Moldex 2200 + 3M 9210		Combined N95 FFR/EV trials Moldex 2300 + 3M 9211	
Measurement	Time (min)	1H (n = 23)	2H (n = 11)	1H (n = 29)	2H (n = 5)[A]
RH (%)	0	63.35 (13.95)	52.70 (13.89)[B]	59.89 (16.39)	66.29 (16.94)
	60	91.41 (8.65)	89.46 (9.02)	87.23 (8.64)	93.01 (7.55)
	120	—	89.60 (10.26)	—	93.31 (8.09)
Temp (°C)	0	31.81 (1.34)	30.63 (1.26)[B]	30.82 (2.09)	31.90 (1.05)
	60	33.89 (0.73)	33.08 (1.32)[B]	32.82 (1.09)	32.77 (1.14)
	120	—	33.26 (1.20)	—	32.77 (0.74)

Notes: Values are presented as mean (SD). Statistical results were based on equal variances assumed and Levene's test for equality of variances for independent samples was not significant ($p>0.05$).
[A]At 2-hr, data from one subject were missing (n = 16).
[B]Significantly different from 1-hr trial.

Downloaded by [Florida Atlantic University] at 11:00 24 November 2014

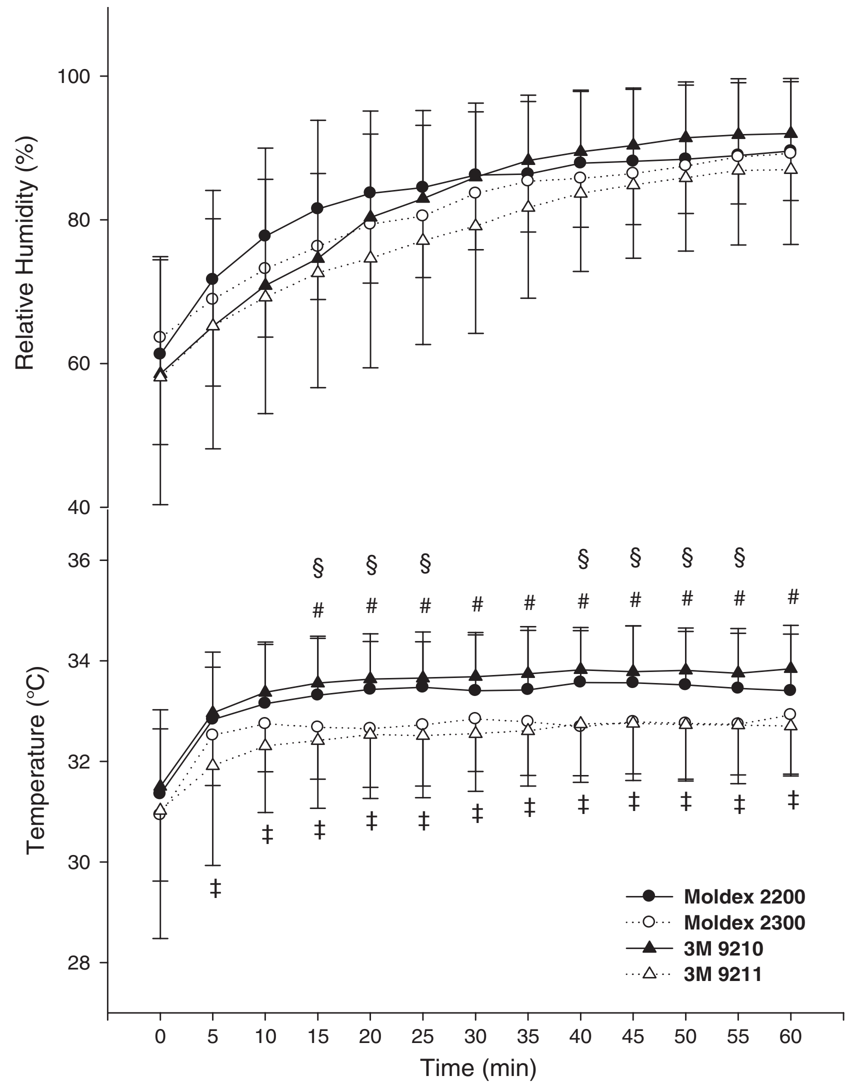


FIGURE 2. Relative humidity and temperature values (presented as mean and SD [n = 17]) §: Moldex 2200 is significantly different from Moldex 2300; # = Moldex 2300 is significantly different from 3M 9216; † : 3M 9216 is significantly different from 3M 9211.

(Figure 2). Time also had a significant effect on temperature ($F = 56.49$; $p < 0.001$) (Figure 2), but the interaction of time and FFR type was not significant ($F = 0.83$; $p = 0.49$). The FFR deadspace temperature values at 120 min were compared with those at 60 min, and no significant differences were noted ($p>0.05$) (Table II).

DISCUSSION

Our data offer a view into the microenvironment of the breathing space (i.e., FFR deadspace) of the N95 FFR wearer. Not surprisingly, the FFR deadspace RH and temperature were markedly higher than ambient levels. Although the FFR deadspace mean air temperatures noted in the current study did not exceed normal nasolabial and perioral skin temperatures found in young adults and older adults,[19] one must additionally consider the impact of the elevated deadspace RH levels on the protective facemask deadspace apparent heat index.[15,20] The apparent heat index is the temperature that the body senses and is a composite effect of heat and humidity.[21] By way of an example, the FFR deadspace air temperature (33.21°C) and RH (89.43%) values, derived as the mean of the four 1-hr values for the FFR models tested (online supplementary Table S-1), equate to a mean FFR deadspace apparent heat index of 54°C.[21] At RPE, deadspace air conditions and ambient temperatures similar to those in the current study, decreases in respiratory heat loss associated with significant changes in ratings of body thermal sensations, increased perceptions of breathing difficulty, and decreased RPE acceptability have been reported.[12,14,22]

N95 FFR/EV were associated with a significant reduction in the deadspace temperature compared with N95 FFR ($p = 0.01$) during the first hour of use. This may be related, in part, to some of the (warmer) end tidal air preferentially

Downloaded by [Florida Atlantic University] at 11:00 24 November 2014

Downloaded by [Florida Atlantic University] at 11:00 24 November 2014

escaping through the open EV rather than being contained in the FFR deadspace. By decreasing the work of breathing, the EV may also decrease breathing exertion-associated increases in metabolic heat. However, prior investigation of N95 FFR and N95 FFR/EV, at a breathing volume of 40 L/min^{-1} over 4 hr and utilizing an Automated Breathing and Metabolic Simulator that mimics human respiration, has shown that an EV results in an average exhalation resistance decrement of only 0.57 mm H_2O pressure compared with no EV.[23]

An EV is activated at a certain breathing pressure threshold, and although the work rate in the present study was a low-moderate one and modern N95 FFR have low breathing resistances, the generated deadspace exhalation pressures must have been sufficient to develop the streamline airflows that (at least partially) opened the EV.[23] Our data indicate that N95 FFR/EV did not convey any significant benefit in terms of deadspace RH at the study work rate. This seems somewhat counterintuitive given the ameliorative effect on deadspace temperature noted in the study. However, moisture in the deadspace is impacted not only by the moisture derived from the exhaled breath but by the sweat that accumulates under the FFR due to impairment of evaporation from the facial skin that is covered by the FFR. In addition, we noted during the trials that exhaled moisture accumulates on the less porous inner surface of the EV, thereby increasing the moisture content in the deadspace region.

Although time had a significant effect on FFR deadspace mean temperature and RH levels in the first hour, this was not manifest in the second hour (Table II). It appears that a plateau effect, wherein continued exertion resulted in no significant increment in FFR deadspace temperature or RH, was achieved for the study work rate during the first hour that continued into the second hour (Figure 2). It appears that steady-state occurs at 10 min and 30 min, respectively, for temperature and humidity (Figure 2). This has potential ramifications for users who might wear FFR for short periods (e.g., health care workers). This steady-state would have been achieved through a balance between metabolic heat production and heat retention effects of the FFR and heat loss mechanisms (e.g., convective and evaporative). Given that it is plausible that most workers would not wear FFR continuously for > 2 hr (due to the usual need for fluids, nourishment, bathroom breaks, and so on), our 2-hr data are reassuring in that they do not show a worsening of the conditions within the FFR deadspace during an extended period of wear.

There was no significant difference in the post-test weights of the N95 FFR compared with N95 FFR/EV following either 1 or 2 hr of continuous use. Weight increase in FFR after their use was likely related to water vapor retention, given that the study site was a physiology laboratory where airborne particulate levels are low in comparison with an industrial work site. The minimal increase in post-test FFR weight observed in the current study is similar to our previous experience,[23–25] and is likely due to the highly hydrophobic nature of polypropylene (the most commonly utilized filter material in modern FFR) and the thinness of modern FFR due to the use of electrically charged (electret) filters that enhance particle collection via electro-attractive forces. The (nonsignificant) greater post-test weight of the N95 FFR/EV compared with the N95 FFR at both 1 hr and 2 hr may be related to (observed) accumulation of moisture on the inner surface of the nonporous EV.

STUDY LIMITATIONS

Limitations of the current study include the small number of FFR models (n = 4) and subjects (n = 17) tested, as well as the fact that we did not test other styles of FFR (e.g., duckbill, pleated). However, we selected FFR from manufacturers with large market shares. Only half the subjects (n = 10) were experienced users; however, the other half are representative of individuals who might wear FFR in rare circumstances (e.g., general population use during a pandemic influenza, while visiting an ill person in a hospital isolation room). We selected a 2-hr work period for comparison rather than a more extended period of time. However, as previously mentioned, given that most workers would not wear FFR continuously for > 2 hr (due to the usual need for fluids, nourishment, bathroom breaks, etc.), we elected to test to a maximum continuous period of 2 hr, as has been done in previous N95 FFR research.[26] Finally, we did not test the FFR under non-temperate ambient environment conditions and thus cannot comment on the impact of such conditions on FFR deadspace heat and RH levels.

The effect of deadspace heat and RH on RPE comfort and tolerance is a complex issue. It has been proposed that RPE comfort is affected primarily by deadspace temperature and RH conditions.[12] Elevated deadspace temperature and humidity may negatively impact RPE tolerance in a number of ways. Skin temperature is dependent on the temperature of the ambient air,[14] which, in the case of RPE, is the deadspace effective heat index that is a composite of deadspace heat and RH.[15,20] The perioral facial skin covered by RPE is especially thermosensitive,[5] possibly due to a higher facial thermoreceptor density, as has been shown in animals.[27] It has been postulated that afferent neural signals from this area might be weighted more than those from other areas in a spatial summation of the total sensory input.[14] Delivery of warm air into a FFR corresponds to application of a thermal stimulus to the perioral skin surfaces and influences whole body thermal sensations.[14]

Also, it has been hypothesized that a countercurrent exchange of heat occurs in the cavernous sinus between cooled venous drainage from the face and warmed arterial blood that supplies brain tissue, including the thermoregulatory center.[12] If the facial skin cannot properly dissipate heat (as occurs in the facial area covered by RPE), the warmed facial venous blood returning to the cavernous sinus may warm the carotid arterial blood and alter the brain temperature. An animal study demonstrated that goats breathing ambient air at 33°C (similar to deadspace air temperatures in the current study) experienced a 0.4°C rise in hypothalamic temperature when the ambient RH was increased from 37% to 96%.[28] A human study utilizing implanted brain thermal sensors has shown

that nasally breathed air (22°C) lowered brain temperature,[29] although the contribution of the air temperature itself has not been fully elucidated. Thus, the heat and RH of the breathing microenvironment (i.e., deadspace) of FFR subjects the wearer to respiration of air with an elevated heat index that warms the FFR-covered facial skin and the inhaled gases, both of which can result in physiological effects that may impact tolerance to wearing FFR. The current study has elucidated the levels of temperature and RH attained in the deadspace of N95 FFR and N95 FFR/EV over the course of 1 and 2 hr. Such data may be useful in assisting in developing strategies and FFR modifications that will help enhance user comfort and, by extension, safety.

CONCLUSION

N95 FFR and N95 FFR/EV use results in FFR deadspace air temperature and RH levels that are markedly elevated above ambient levels and are associated with a significant deadspace heat index. At a low-moderate work rate, N95 FFR/EV use resulted in significantly lower deadspace air temperature over 1 hr of continuous wear but offered no advantage in deadspace humidity dissipation. Moisture retention in N95 FFR and N95 FFR/EV is minimal after 1 and 2 hr of continuous use at a low-moderate work rate.

Downloaded by [Florida Atlantic University] at 11:00 24 November 2014

ACKNOWLEDGMENT

The authors thank Ed Fries, William Newcomb, and Drs. Ronald Shaffer and W. Jon Williams for their review of the manuscript and helpful suggestions.

REFERENCES

1. "Respirator Usage in Private Sector Firms, 2001." [Online] Available at http://www.cdc.gov/niosh/docs/respsurv/pdfs/respsurv2001.pdf (accessed March 4, 2011).
2. **Martyny, J., C.D. Glazer, and L.S. Newman:** Respiratory protection. *N. Engl. J. Med. 347*(*11*):824–830 (2002).
3. **Hanson, R. de G.:** Respiratory heat loss at increased core temperature. *J. Appl. Physiol. 37*(*10*):103–107 (1974).
4. **Harber, P., J. Beck, C. Brown, and J. Luo:** Physiologic and subjective effects of respirator mask type. *Am. Ind. Hyg. Assoc. J. 52*:357–362 (1991).
5. **Laird, I.S, R. Goldsmith, R.J. Pack, and A. Vitalis:** The effect on heart rate and facial skin temperature of wearing respiratory protection at work. *Ann. Occup. Hyg. 46*(*2*):143–148 (2002).
6. **Pretorius, T., G.K. Bristow, A.M. Steinman, and G.G. Giesbrecht:** Thermal effects of whole head submersion in cold water on nonshivering humans. *J. Appl. Physiol. 101*(*2*):669–675 (2006).
7. **Hayashi, C., and H. Tokura:** The effects of two kinds of mask (with or without exhaust valve) on clothing microclimates inside the mask in participants wearing protective clothing for spraying pesticides. *Int. Arch. Occup. Environ. Health 77*(*1*):73–78 (2004).
8. **Li, Y., H. Tokura, Y.P. Guo, et al.:** Effects of wearing N95 and surgical facemasks on heart rate, thermal stress and subjective sensations. *Int. Arch. Occup. Environ. Health 78*(*6*):501–509 (2005).
9. **Guo, Y.P., L. Yi, H. Tokura, et al.:** Evaluation of masks with exhaust valves and with exhaust holes from physiological and subjective responses. *J. Physiol. Anthropol. 27*(*2*):93–102 (2008).
10. **Laird, I., R. Pack, and D. Carr:** A survey on the use and non-use of respiratory protective equipment in workplaces in a provincial New Zealand city. *Ann. Occup. Hyg. 37*(*4*):367–376 (1993).
11. **Baig, A., C. Knapp, A.E. Eagan, and L.J. Radonovich Jr.:** Health care workers' views about respirator use and features that should be included in the next generation of respirators. *Am. J. Infect. Control 38*:18–25 (2010).
12. **Gwosdow, A.R., R. Nielsen, L.G. Berglund, A.B. DuBois, and P.G. Tremml:** Effect of thermal conditions on the acceptability of respiratory protective devices on humans at rest. *Am. Ind. Hyg. Assoc. J. 50*:188–195 (1989).
13. **Bailar, J.C., L.M Brosseau, H.J. Cohen, et al.:** *Reusability of Facemasks during an Influenza Pandemic.* Washington, D.C**:** IOM, National Academies Press, 2006.
14. **Gwosdow, A.R., and A.B. DuBois:** Thermal sensation of the body as influenced by the thermal microclimate in a face mask. *Ergonomics 30*(*12*):1689–1703 (1987).
15. **Jones, J.G.:** The physiological cost of wearing a disposable respirator. *Am. Ind. Hyg. Assoc. J. 52*:219–225 (1991).
16. "Better Respiratory Equipment Using Advanced Technologies for Healthcare Employees (Project BREATHE)- FY10." [Online] Available at http://www.cdc.gov/niosh/nas/ppt/QUADCharts10/ZJVY_FY10_QC.htm (accessed April 26, 2011).
17. "Occupational Safety and Health Standards, Respiratory Protection Standard 1910.134." (1998) [Online] Available at http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_id = 12716&p_table = standards (accessed April 26, 2011).
18. **Davis, R.R., and P.B. Shaw:** Heat and humidity buildup under earmuff-type hearing protectors. *Noise Health 13*(*51*):93–98 (2011).
19. **Marrakachi, S., and H.I. Maibach:** Biophysical parameters of skin: Map of human face, regional, and age-related differences. *Contact. Derm. 57*:28–34 (2007).
20. **Enerson, D.M., L.I. Eisenfeld, and H. Kajikuri:** Heat and moisture trapping beneath surgical face masks: A consideration of factors affecting the surgeon's discomfort and performance. *Surgery 62*(*6*):1007–1016 (1967).
21. "Meteorological Conversions and Calculations, Heat Index Calculator." [Online] Available at http://www.hpc.ncep.noaa.gov/html/heatindex.shtml. (accessed April 26, 2011).
22. **Nielsen, R., A.R. Gwosdow, L.G. Berglund, and A.B. DuBois:** The effect of temperature and humidity levels in a protective mask on user acceptability during exercise. *Am. Ind. Hyg. Assoc. J. 48*:639–645 (1987).
23. **Roberge, R.J., E. Bayer, J.B. Powell, A. Coca, M.R. Roberge, and S.M. Benson:** Effect of exhaled moisture on breathing resistance of N95 filtering facepiece respirators. *Ann. Occup. Hyg. 54*(*6*):671–677 (2010).
24. **Roberge, R.J., A. Coca, W. J. Williams, J.B. Powell, and A.J. Palmiero:** Physiological impact of the N95 filtering facepiece respirator on healthcare workers. *Resp. Care 55*(*5*):569–577 (2010).
25. **Roberge, R.J., A. Coca, W.J. Williams, A.J. Palmiero, and J.B. Powell:** Surgical mask placement over N95 filtering facepiece respirators: Physiological effects on healthcare workers. *Respirology 15*:516–521 (2010).
26. **Radonovich Jr., L.J., J. Cheng, B.V. Shenal, M. Hodgson, and B.S. Bender:** Respirator tolerance in health care workers. (Research Letter). *J. Am. Med. Assoc. 301*(*1*):36–38 (2009).
27. **Cheung, S.S.:** Interconnections between thermal perception and exercise capacity in heat. *Scand. J. Med. Sci. Sports 20*(*Suppl 3*):53–59 (2010).
28. **Jessen, C., and H. Pongratz:** Air humidity and carotid rete function in thermoregulation of the goat. *J. Physiol. 292*:469–479 (1979).
29. **Mariak, Z., M.D. White, J. Lewko, T. Lyson, and P. Piekarski:** Direct cooling of the human brain by heat loss from the upper respiratory tract. *J. Appl. Physiol. 87*:1609–1613 (1999).